Distributed Wireless Multi-sensor Technologies

DOE Contract: DE-FC36-04GO14001
CPS #14226

Daniel Sexton
General Electric Global Research

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

Presentation Overview

- Project Overview/Summary
- Technical Metrics and Barriers
- Progress to date
- Future Plans
- Commercialization

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

Goals/Challenges/Benefits

CPS #14226

Goal: Wireless multi-sensors that can be deployed in an industrial environment to facilitate better maintenance practices for improved energy performance.

Challenge: Low-life cycle cost and robust wireless communications. Customer acceptance.

Benefits: One potential use: more efficient operation of electric motors through early identification of potential failures resulting in an estimated savings of 0.1 Quads of Electricity by 2020.

FY04/05 Activities: Collect customer requirements, using various industrial sites, characterize the RF environment, build statistical models to verify system performance, retire high risk technology items and perform system design.

Participants:

Sensicast Systems, Needham MA.
Rensselaer Polytechnic Institute, Troy NY.
Chevron Texaco, Houston Tx.

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

Distributed Wireless Multi-sensor Technologies CPS # 14226

Barrier-Pathway Approach

Barriers

- Noisy unreliable channel
- Short battery life
- Life cycle costs
- Network Security
- Gateways

Pathways

- Characterize the channel, qualify a design approach.
- Low duty cycle operation, energy harvesting.
- Minimize device cost, maximize life and reduce installation expense
- Data Encryption
- Standard Interfaces

Critical Metrics

- Accurate early prediction of asset faults before they occur
- 5 year average unattended life
- Significant reduction in installed costs.

Benefits (est.)	2020
Energy Savings	122 trillion Btu
Cost Savings	TBD
Carbon Reduction	2.13 MMTCe

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

Project Overview

Low-Cost Wireless Multi-Measurand Sensing Program

Wireless Sensor Concept

Sensor Housing — Seal — Mount — Electronics — Battery

Advantages
- Communication reliability
- Long life (minimum 3 years)
- Robust package (-40˚C–70˚C operation)
- No FCC license required (ISM band)
- Multiple sensor options in single package
- Enclosure options suitable for outdoor applications

Benefits of the Technology
- Estimation of remaining life
- Indicator of operational efficiency
- Improves asset maintenance strategies

Low-Cost Wireless Sensors

Router
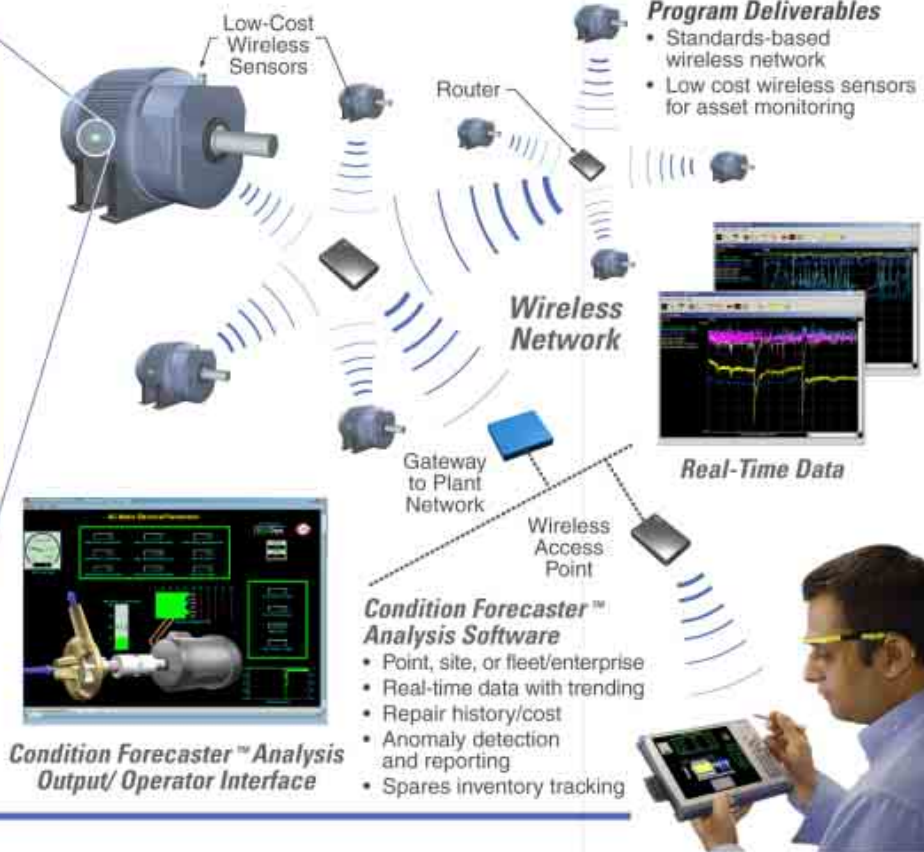
Program Deliverables
- Standards-based wireless network
- Low cost wireless sensors for asset monitoring

Wireless Network

Gateway to Plant Network

Wireless Access Point

Real-Time Data

Condition Forecaster™ Analysis Software
- Point, site, or fleet/enterprise
- Real-time data with trending
- Repair history/cost
- Anomaly detection and reporting
- Spares inventory tracking

Condition Forecaster™ Analysis Output/ Operator Interface

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

GRC External Team Members

GE Industrial Systems

- 50% cost share commitment
- Sensor Commercialization

Sensicast

- MAC and Networking Software
- Network configuration tools
- 50% cost share commitment

Chevron TEXACO

- Customer requirements
- Onsite testing and qualification

Power Systems

- Condition Forcaster^{TM}
- Commercialization through Service Business

Rensselaer

- Advanced motor condition modeling
- Sensor to condition identification

Daniel Sexton
GE Global Research
June 21st 2004
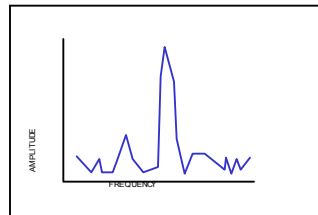
imagination at work

Progress to Date

Customer Requirements

- Customer Interviews
- Customer Surveys

Channel Capability Analysis

- Channel Characterization
- Simulation Models
- Physical Channel model

Technology Selection

- Radio Technology
  Experimental Data
  Vendor Selection
- Networking Technology
  Partner Selection
- Processor Technology
  Device Selection
- Energy Source
  Study options
  Experimental data

imagination at work

Voice of the Customer

• Conducting one on one customer interviews with different industries

• Developed Web based Conjoint survey.

• Distributed over 50 paper surveys to various industries

• Data collection ongoing, too early for requirements analysis.

http://www.sawsft.com/~mvm/MVM/cgi-bin/ciwweb.pl - Microsoft Internet Explorer provided by ITMS @ GE Global Research

File   Edit   View   Favorites   Tools   Help

Back   Search   Favorites   Media

Address   http://www.sawsft.com/~mvm/MVM/cgi-bin/ciwweb.pl

If these were your only options, which would you choose?
Choose by clicking one of the buttons below

Price per motor *See Definition*	$450 per motor (One Time)	$450 per motor (One Time)	$950 per motor (One Time)	Price per motor per year equals:$1,000 (Recurs annually)
Anomaly Coverage *See Definition*	Bearing Health - Vibration Thresholds	Bearing Health - Multiple measures **Insulation Health - Multiple measures**	Bearing Health - Multiple measures **Insulation Health - Multiple measures** **Mechanical Health - multiple measures**	**Mechanical Testing Standard** 1. Vibration taken once a month 2. Accomplished via a Walkaround 3. Analysis/Report done Manually 4. Data Logged into Database for trending & Viewing 5. Assumes 25 motor route per day
Condition Trending *See Definition*	Once a second	Once a minute	Remote programmable (Daily/Hourly/Minute or Second)	**Electrical Testing Standard** 1. Megger & PI test once every 6 months
Reliability & Maintainability *See Definition*	MTBF:6 years (Sensor) MTBI:3 years (System)	MTBF:2 years (Sensor) MTBI:1 year (System)	MTBF:6 years (Sensor) MTBI:3 years (System)	2. Accomplished via a Walkaround 3. Analysis/Report done Manually 4. Data Logged into Database for trending & Viewing
Data Analysis *See Definition*	Condition Monitoring (Trending/Anomaly) **Health Assessment (Stressed Component)**	Condition Monitoring (Trending/Anomaly) **Health Assessment (Stressed Componet)** **Prognostics (Remaining Life)** **Decision Support (Advisory)**	Condition Monitoring (Trending/Anomaly)	5. Assumes 10 motor route per day 6. Requires shutdown to access equipment Pricing Based on 1 1/2 days per
Power Requirements *See Definition*	Sensor (Self powered w/battery) Router (direct source)	Sensor & Router (direct source)	Sensor (Self powered w/battery) Router (direct source)	month for Mechanical & 7 Total Days for electrical testing. Assumes a $1,000 daily cost including T&L.
Local or Remote *See Definition*	Centralized Customer Server	Local Site Server - No Remote Access	GE Supported Server	**The above reflects Standard Option Preventative Maintance Program**
Data Security *See Definition*	None	Rotating Key Updates (Includes both Encryption & Authentication)	Encryption	
	○	○	○	○

Please click on radio button above that reflects the product you would likely purchase

Internet

Online Conjoint Survey

Medium Voltage Motors: http://www.sawsft.com/~mvm/MVM/MVMlogn.htm
Low Voltage Motors: http://www.sawsft.com/~mvm/LVM/LVMlogn.htm

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

ChevronTexaco

✓Large Population (85%) under 200HP
✓Bearings most common failure on Low voltage
✓Proper Packaging is a must have
✓Many outdoor applications
✓Reasonable system costs a must

AIR LIQUIDE

✓Mobility of sensing packing & platform highly desirable
✓Additional assets/application focus very desirable (Motor-Pump)
✓No packaging restrictions
✓Comm readily accessible, 100Ft-100ft

Common Customer Inputs

Reasonable Cost of Implementation
Adequate Set of "Predictive" Sensed Functions
Ease of Use & Reliability of System
Maintenance/Engineering Decision Support
Network Security (Gateway in particular)
Ability to integrate with Suite of Existing Software & assets
Scalability & Extensibility of wireless network
Proper Packaging

PPG Industries Corporate

✓Motor Energy costs small % of total
✓95% motors under 200HP
✓Un spared (other) applications most desirable
✓Low sensor cost
✓Packaging a must, outdoors, 100m, 1/day transmission,

SUNOCO

✓Network Security
✓Adequate sensing functions
✓Reasonable cost
✓Effectiveness of Network
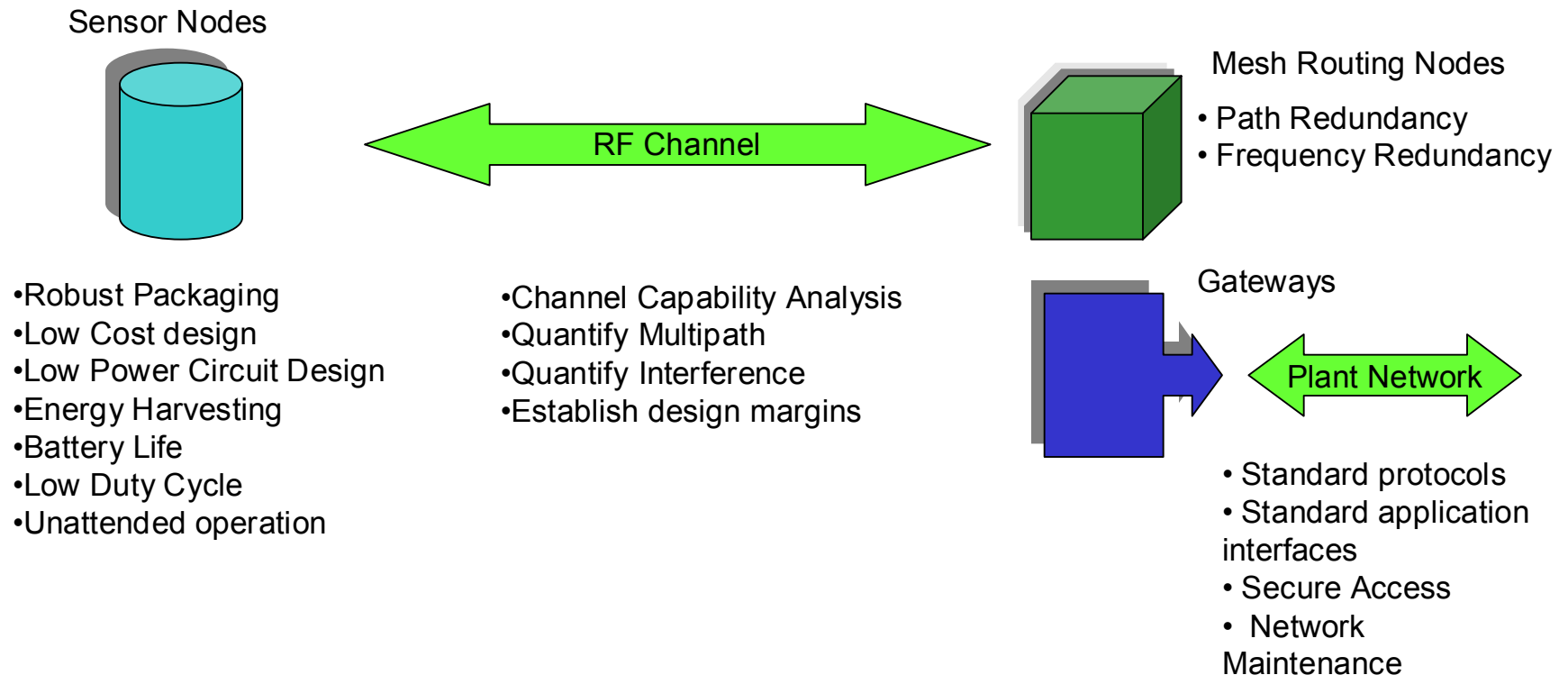✓Ability to integrate w/ existing software/assets

Timken Latrobe Steel
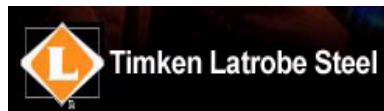
✓Adequate sensing functions
✓Motor reliability with life prediction essential
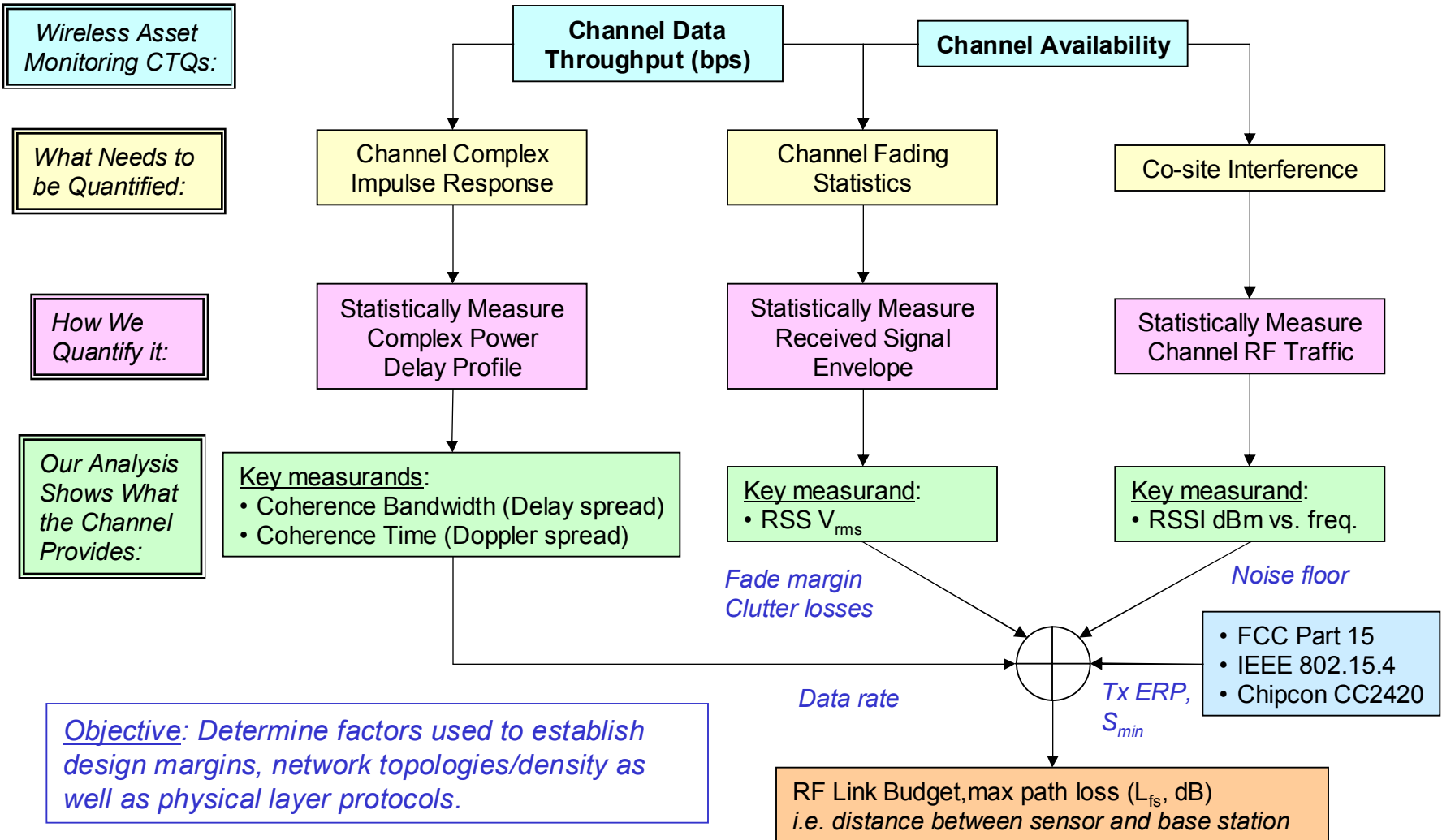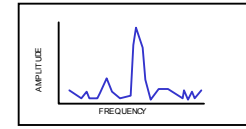✓Immediate motor replacement advise

VALERO ENERGY CORPORATION

✓Adequate "Predictive" sensing functions
✓Reasonable cost
✓Ease of installation
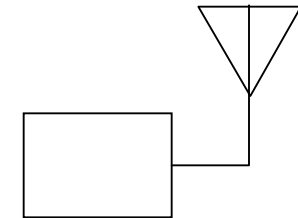✓Ability to integrate with existing software/assets

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

System Mapping of Technology Needs

Sensor Nodes

RF Channel

Mesh Routing Nodes

• Path Redundancy
• Frequency Redundancy

•Robust Packaging
•Low Cost design
•Low Power Circuit Design
•Energy Harvesting
•Battery Life
•Low Duty Cycle
•Unattended operation

•Channel Capability Analysis
•Quantify Multipath
•Quantify Interference
•Establish design margins

Gateways

Plant Network

• Standard protocols
• Standard application interfaces
• Secure Access
• Network Maintenance

imagination at work

Channel Capability Analysis

Wireless Asset Monitoring CTQs:

Channel Data Throughput (bps)

Channel Availability

What Needs to be Quantified:

Channel Complex Impulse Response

Channel Fading Statistics

Co-site Interference

How We Quantify it:

Statistically Measure Complex Power Delay Profile

Statistically Measure Received Signal Envelope

Statistically Measure Channel RF Traffic

Our Analysis Shows What the Channel Provides:

Key measurands:
• Coherence Bandwidth (Delay spread)
• Coherence Time (Doppler spread)

Key measurand:
• RSS V_{rms}

Key measurand:
• RSSI dBm vs. freq.

Fade margin
Clutter losses

Noise floor

Data rate

• FCC Part 15
• IEEE 802.15.4
• Chipcon CC2420

Tx ERP, S_{min}

Objective: Determine factors used to establish design margins, network topologies/density as well as physical layer protocols.

RF Link Budget, max path loss (L_{fs}, dB)
i.e. distance between sensor and base station

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

2.4 GHz Channel Complex Impulse Response

Berkeley Varitronics
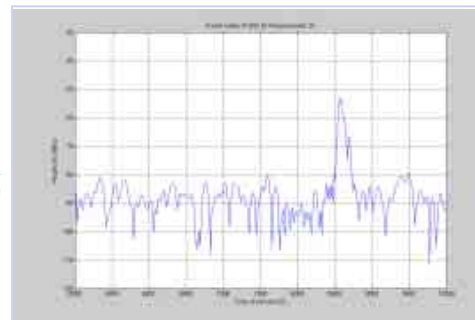Systems
Raptor XMTR

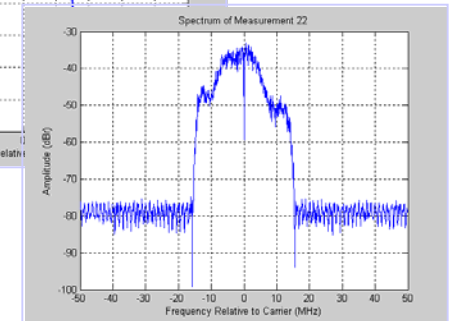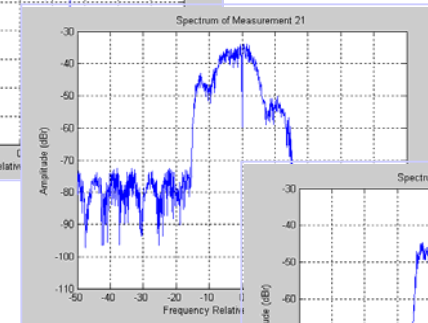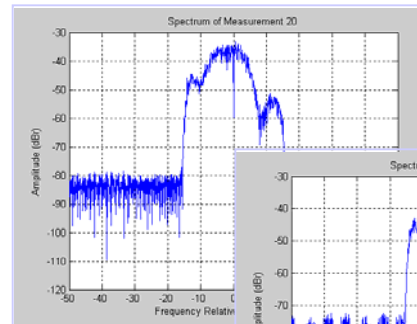*Transmit and receive
2.4 GHz ISM-band
Complex DSSS Signal*
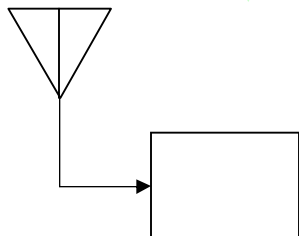
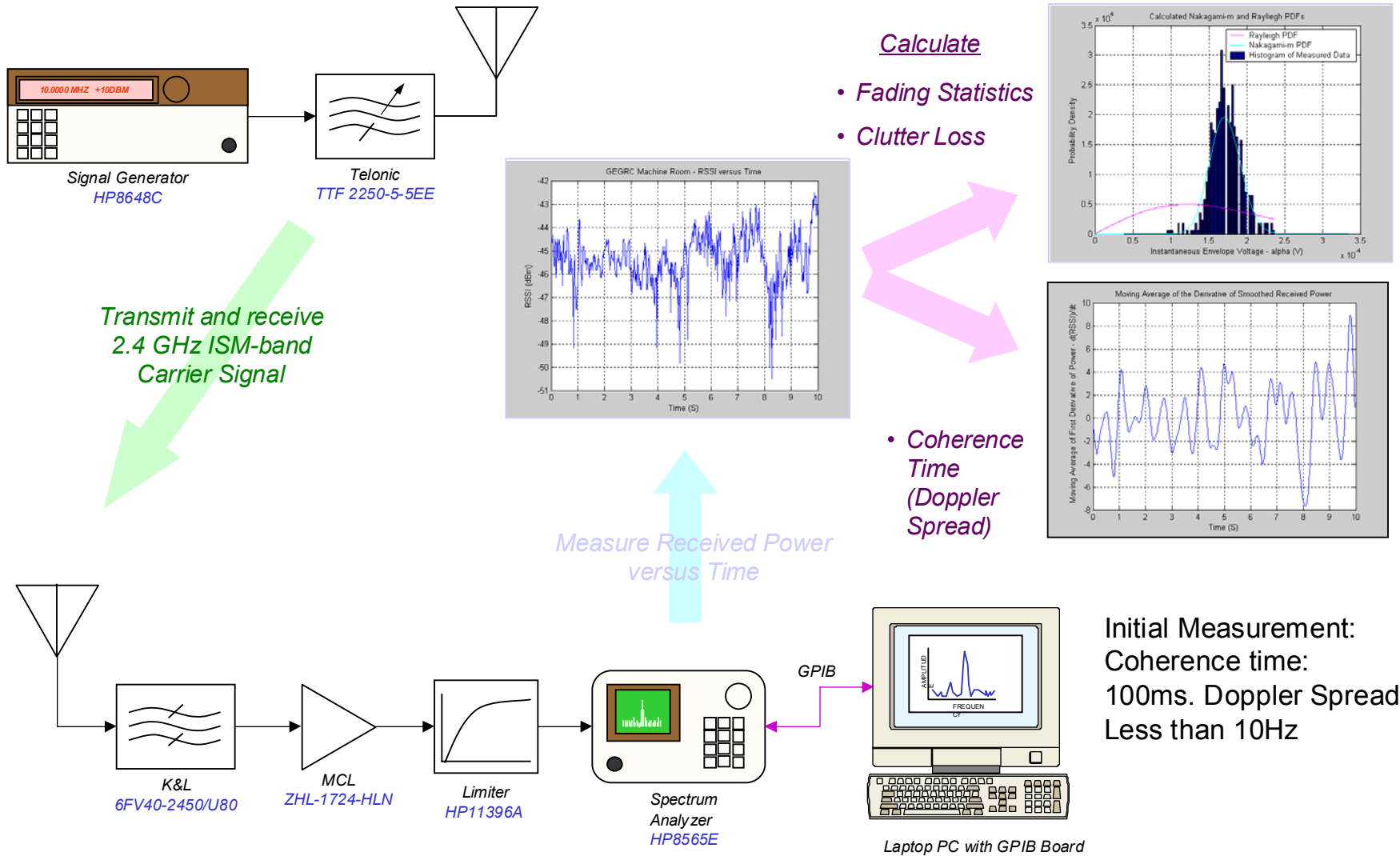Berkeley Varitronics
Systems
Raptor RCVR

*Measure
Power Delay Profile
(channel impulse response)
versus Time*

Calculate

Coherence
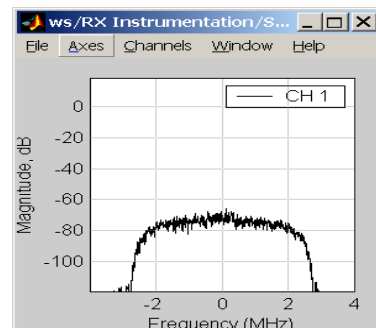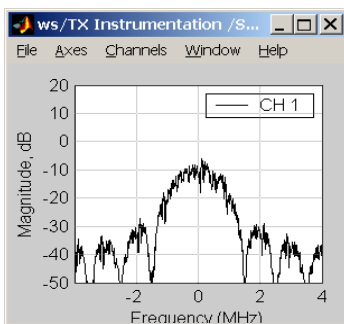Bandwidth (Delay
Spread) variations
over time

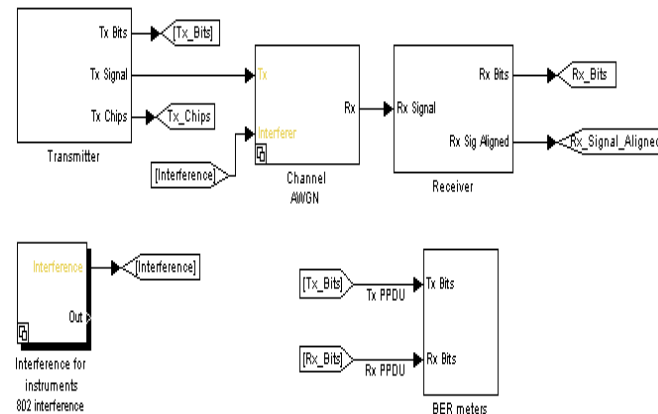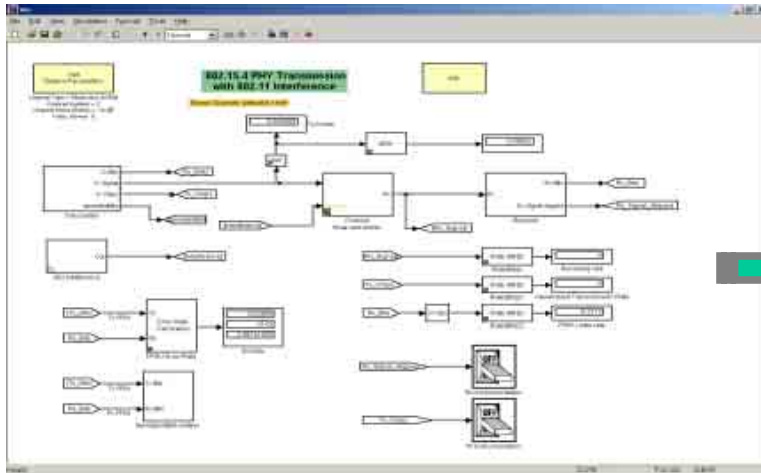Initial Measurement (1 site, one time):
Coherence BW 250kHz –
10 MHz
More data must be collected

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

2.4 GHz Channel Coherence Time and Fading Statistics

Signal Generator
HP8648C

Telonic
TTF 2250-5-5EE

Transmit and receive
2.4 GHz ISM-band
Carrier Signal

<u>Calculate</u>

• Fading Statistics

• Clutter Loss

• Coherence Time (Doppler Spread)

Measure Received Power versus Time

K&L
6FV40-2450/U80

MCL
ZHL-1724-HLN

Limiter
HP11396A

Spectrum Analyzer
HP8565E

GPIB

Laptop PC with GPIB Board

Initial Measurement: Coherence time: 100ms. Doppler Spread Less than 10Hz

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

802.15.4 Matlab Simulink Model

– 802.15.4 PHY model was built and simulated with Matlab and Simulink

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

Physical Channel Simulator

Shielded Enclosure #1

Sensor Receiver
Test System

R. L. Frey
2/13/2004

Testing Capabilities

- Radio Qualification Studies
- Receiver Sensitivity
- Transmitter properties
- Straight multipath
- Multipath with Rayleigh fading
- Interference studies
- Coexistence studies

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work
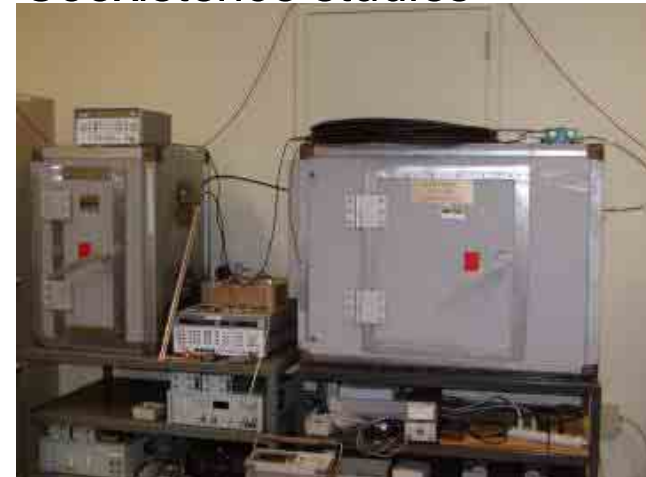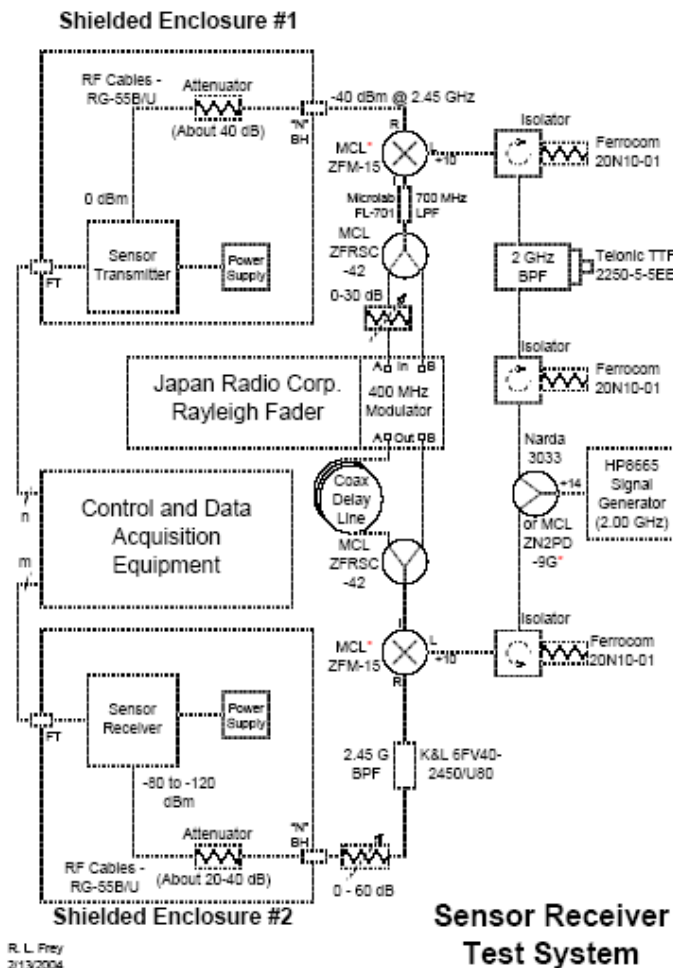
Radio Testing

- Prototyped radio design with +15dBm transmitter.
- Built multiple radio nodes for onsite radio performance data collection.
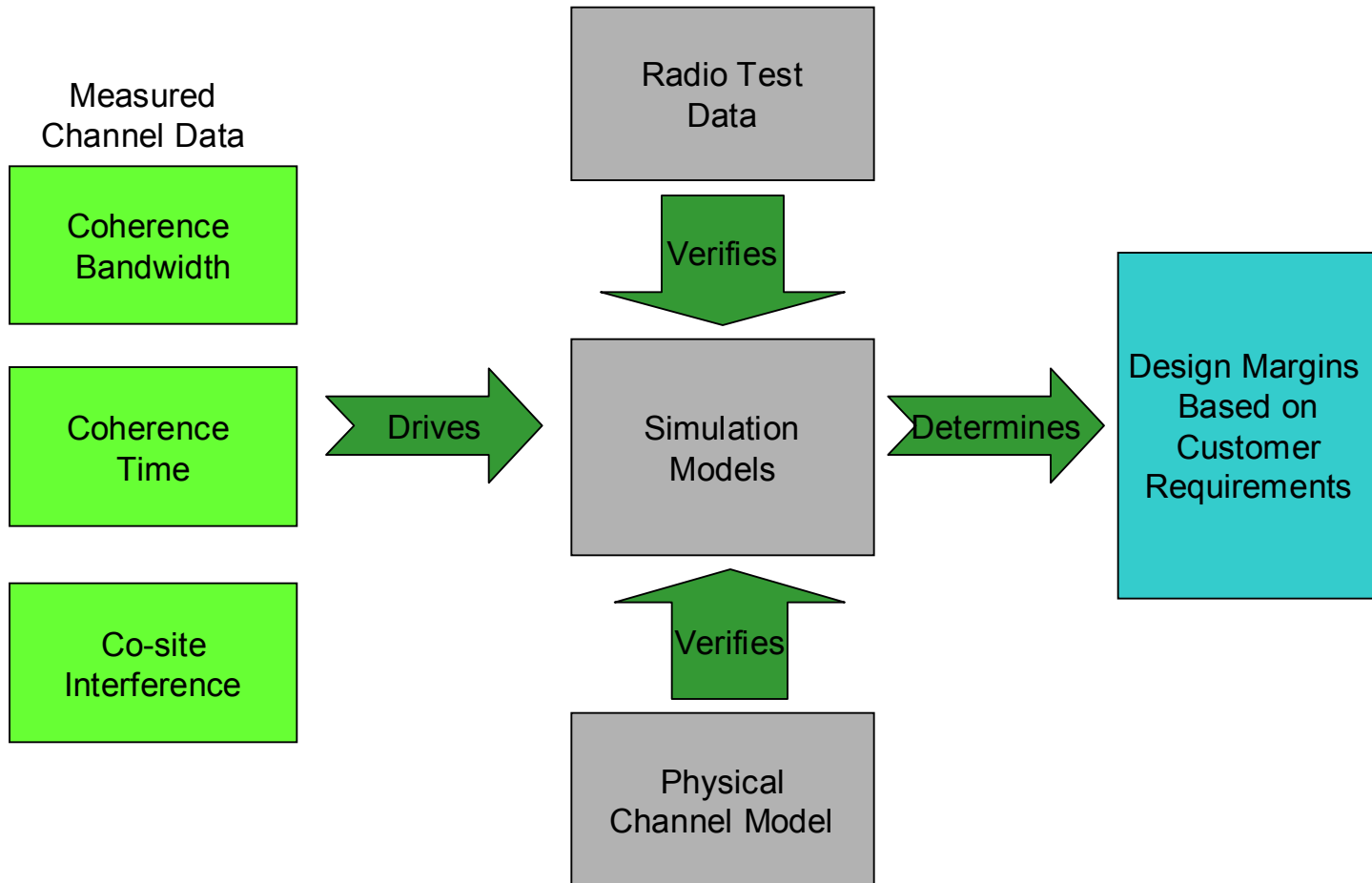- Testing in representative Industrial Environments


GE Onsite test bed

Radio Performance Analysis

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

Channel Capability Analysis Flow

Six Sigma Approach to Robust Design

imagination at work

Sensimesh is self-configuring

Unique Features:
- Two Way Communications
- Over the air programming
- Channel Agile
- Redundant paths
- Network Gateway

- Power efficient routing nodes
- Network management software
- Simple device configuration
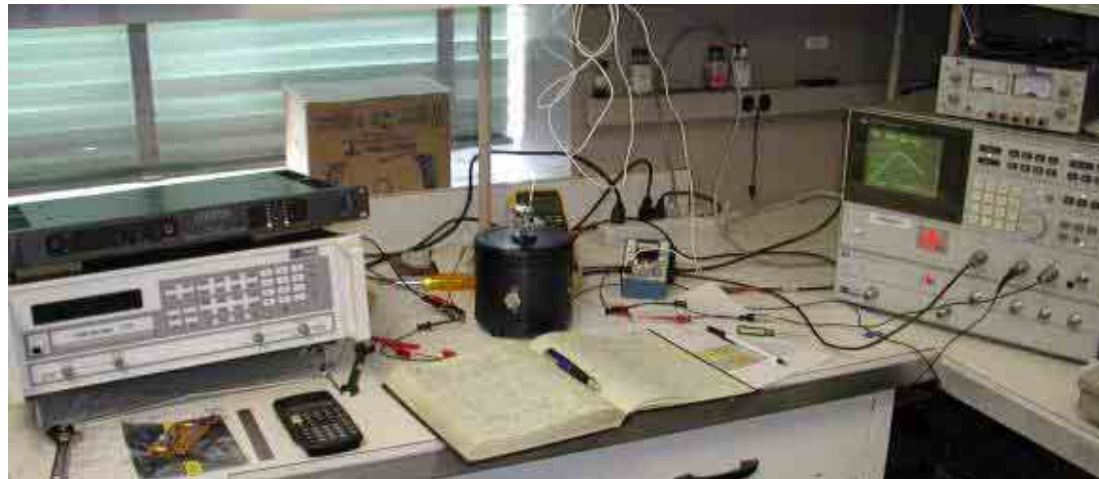- Encryption Key Distribution

Any wired network

Daniel Sexton
GE Global Research
June 21st 2004
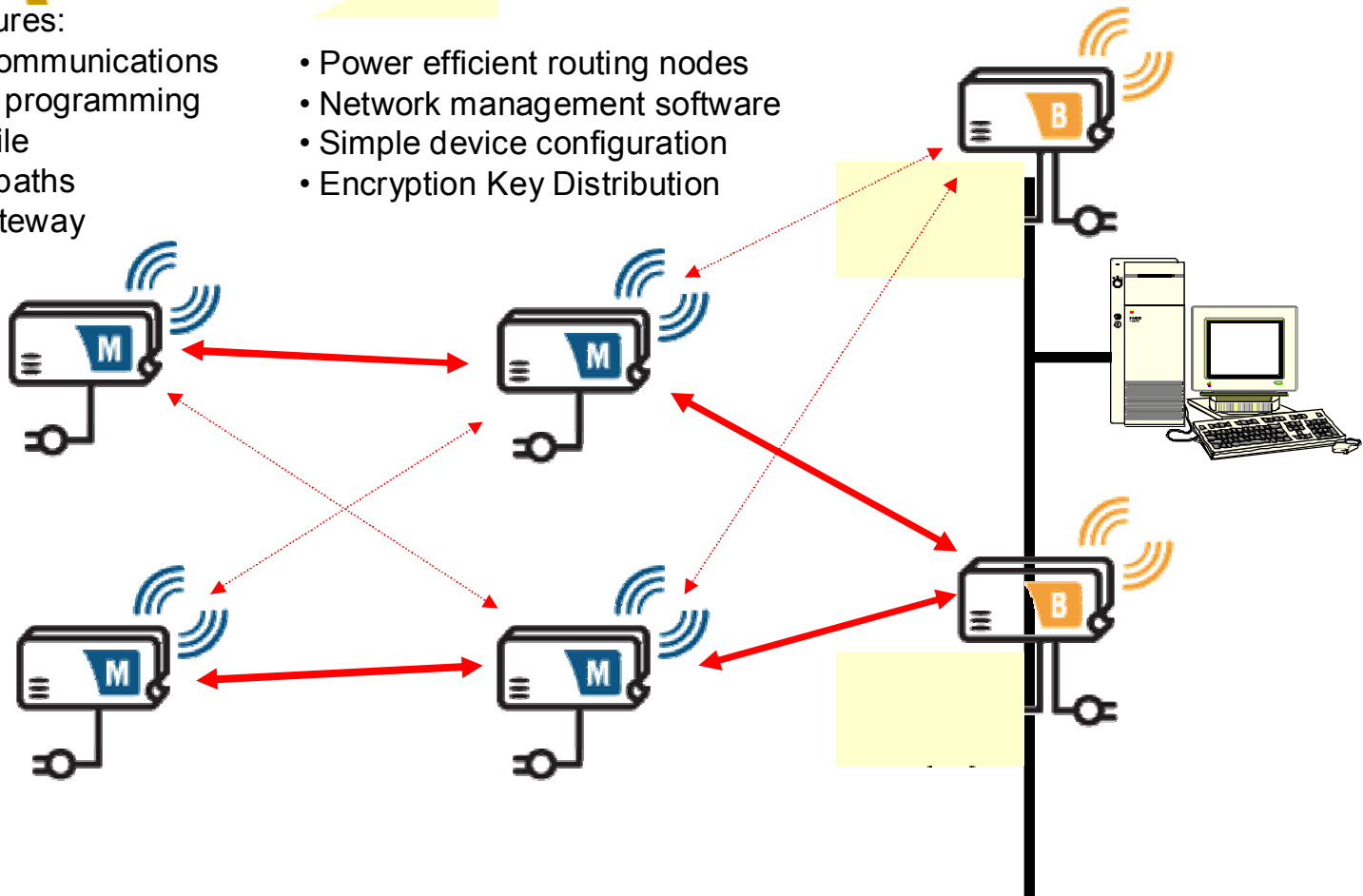
imagination at work
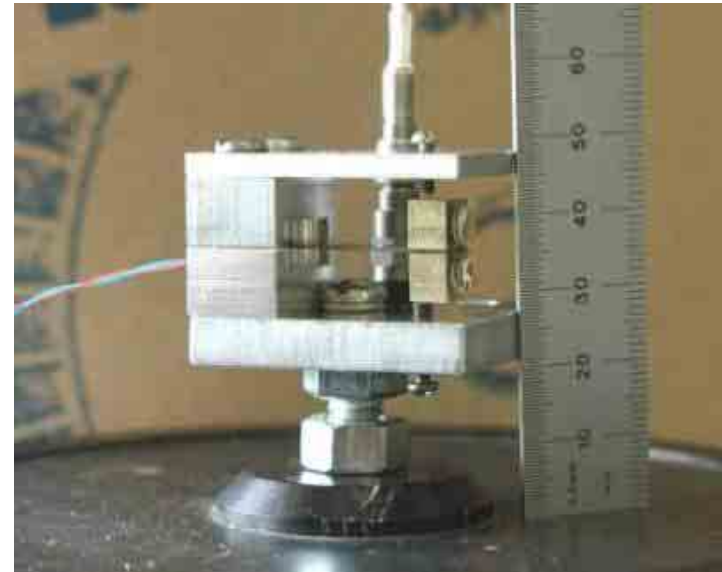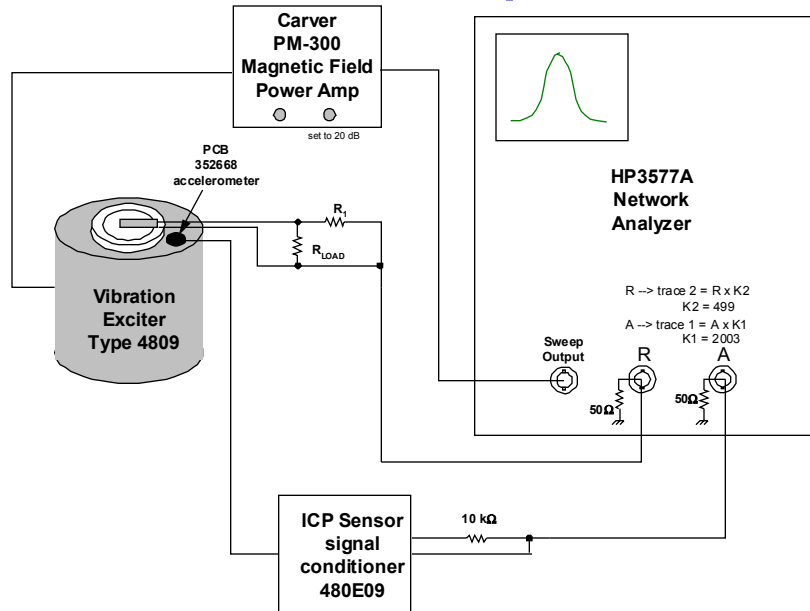
Sensor Energy Source Study

- Battery technology qualification and reliability study underway

- Lab experiments with prototype harvesting circuit underway

- GE Energy Services database data reduction for 2-pole, 60Hz motors (estimates for available energy from vibrations)

- Modeling of piezoelectric beam generators

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

Experimental Setup

Carver PM-300 Magnetic Field Power Amp

set to 20 dB

PCB 352668 accelerometer

R_1

R_{LOAD}

Vibration Exciter Type 4809

HP3577A Network Analyzer

R --> trace 2 = R x K2
K2 = 499
A --> trace 1 = A x K1
K1 = 2003

Sweep Output

R   A

50 Ω   50 Ω

ICP Sensor signal conditioner 480E09

10 kΩ

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

Available Motor Vibration Data

- GE Energy Services Database,

  Customer Databases

- Data for 31 different

  AC motors extracted

- 824 data points extracted for those motors
  - Some motors monitored once, 2 monitored on ~40 dates
  - Motors usually have at least 2 horizontal and 2 vertical measurements

- Limiting data to 2-pole machines

- Analysis of fleet data in process, determining available energy level versus percentage of motors covered.

imagination at work

Condition Forecaster^{TM}

Technology elements are available to predict remaining motor life, given:

- Continuous sensor data,

- Historical repair data with mechanism in place to collect comprehensive data,

- Expert knowledge of root cause, and

- Data fusion between historical and real time sensor data to augment reliability statistics.
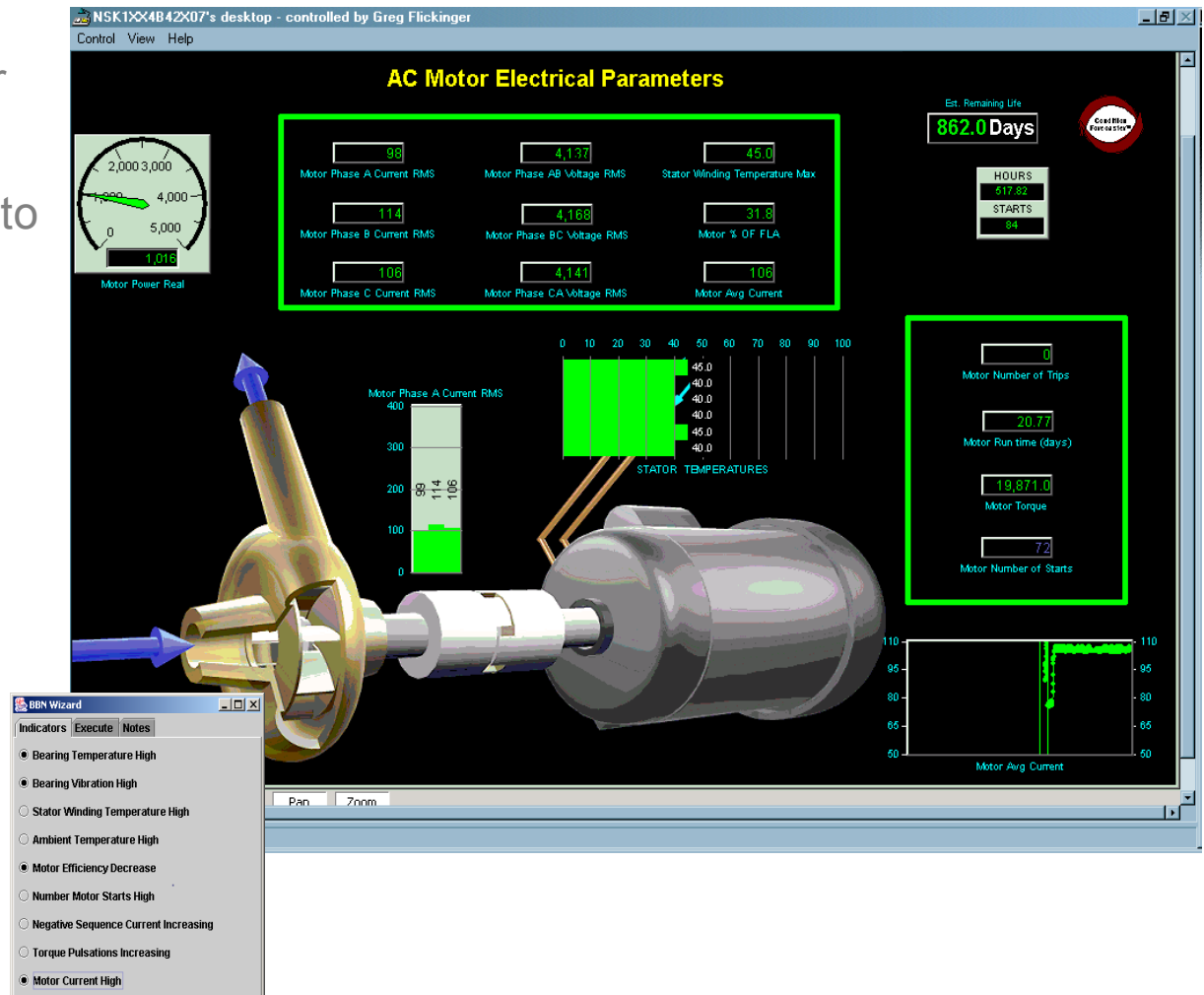

Data Fusion with existing components
- ❖   Protective relays can provide:
1. Current measurements/waveforms
2. Voltage measurements/waveforms
3. Power quality analysis

Daniel Sexton
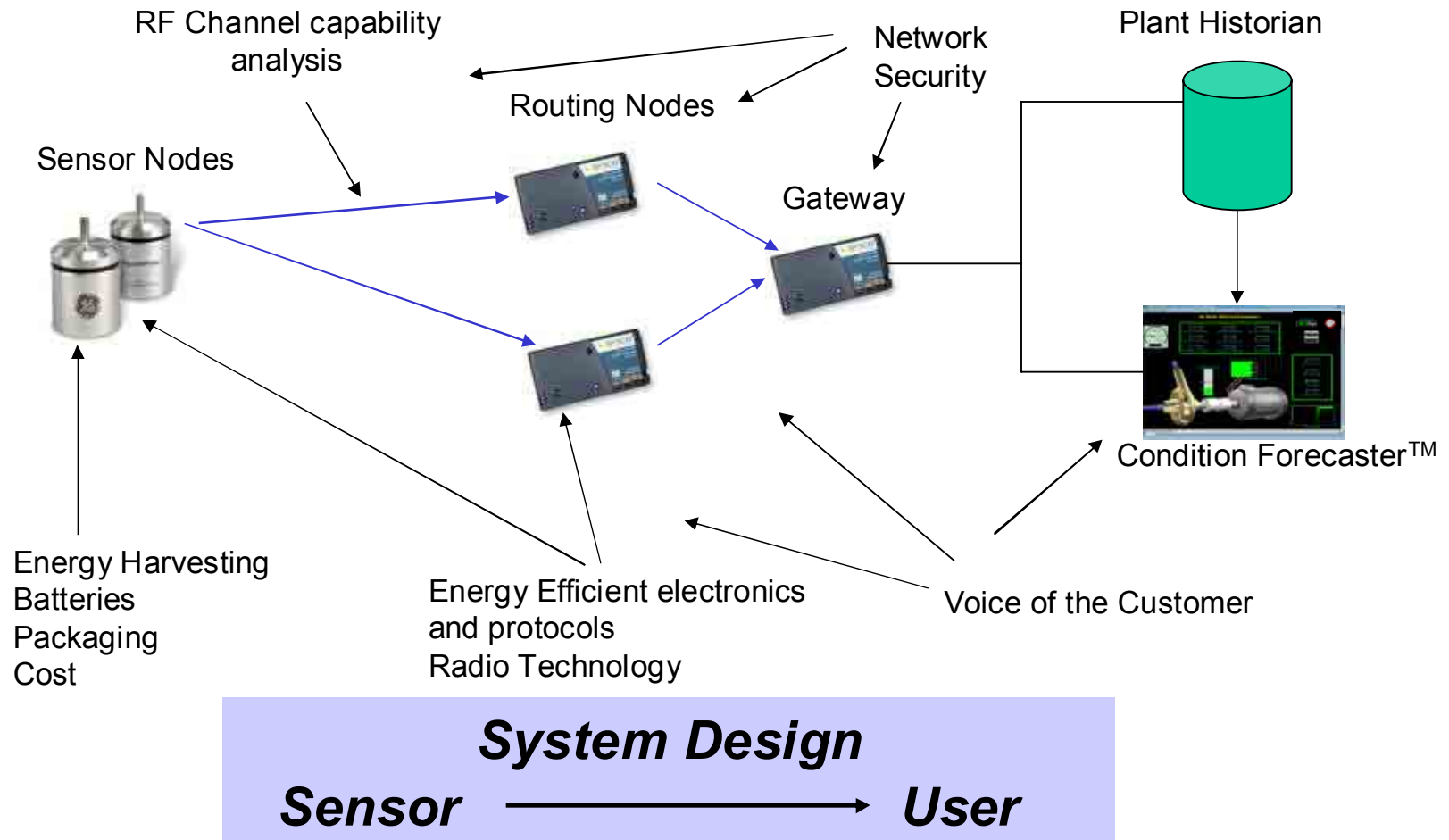GE Global Research
June 21st 2004

imagination at work

Motor Reliability Analysis Output

The Condition Forecaster analysis outputs:

- Most likely component to experience next failure and the associated probability,

- Time until failure (in days) bounded by a statistical confidence interval, and

- Current sensory data.

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

Project Activity Summary

RF Channel capability analysis

Network Security

Plant Historian

Sensor Nodes

Routing Nodes

Gateway

Condition Forecaster™

Energy Harvesting
Batteries
Packaging
Cost

Energy Efficient electronics
and protocols
Radio Technology

Voice of the Customer

System Design

Sensor ⟶ **User**

imagination at work

Future Plans - Next 12 months

Voice of the Customer

- Complete Customer conjoint surveys/analyze data

Capability Analysis

- Collect Channel/Radio Characteristics – multiple field sites
- Sample motor vibration data – multiple customer sites
- Battery life testing and qualification testing

Onsite Technology Qualification

- Quantify Energy Harvesting capability
- Refine System design based on data collected
- Port Sensicast MAC and network software to CC2420
- Build alpha units and deploy at customer sites
- Build Alpha Gateway for interface to Plant Historian and *Condition Forecaster*^{TM}
- Begin integration with *Condition Forecaster*^{TM}

Future Optimization

- Initiate motor physical modeling improvements at RPI

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work

Commercialization

- GE Infrastructure engaged, commercial license agreement with Sensicast under negotiation.

- Sensicast contributing member to ZigBee – standards being influenced.

- GE Kaye Instruments studying packaging/Production options based on ValProbe product (Class I Div II package)

- GE Energy (Bently Nevada and GE Energy Services) to incorporate *Condition Forecaster^{TM}* into *System One^{TM}* -- market to industrial customer base. Sales and marketing teams engaged.

- Wireless Technology being leveraged by other GE Businesses – Security (Interlogix), Building Automation (GE Lighting), Utilities (GE Multilin).

This project is a positive driver for making wireless sensors a reality

Daniel Sexton
GE Global Research
June 21st 2004

imagination at work